Tensile and Compressive Behaviour of Early Age Concrete

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ABSTRACT

Concrete is relatively weak in tension, but this should not mean the tensile capacity should be ignored, it still has an important role to play when considering early age concrete properties, especially when you are considering lifting at an early concrete strength. The more efficient and sophisticated design techniques become, the better the understanding of material properties needs to be, and in the case of tensile properties the interest is in relation to the cracking behaviour.

The adopted test method used in this paper is the less commonly applied direct tension method. This test was not established to redefine a new test regime, but to research the relevance of this test method. This method has been considered a more direct concrete tension representation when considering the capacity of early age concrete. It has overcome the difficulties of centralizing and aligning the specimen, which is inherent in other test methods. Two concrete mixes were used, which represent typical mixes used in the precast industry. These were selected to study the effects of age, compressive strength gain, and the relative tensile strain capacity.

The significance of understanding the behaviour of concrete in tension is detailed and the role of tensile properties with fracture mechanisms is explored. It is shown that the relationship between tensile strength is independent of compressive strength gain, mix composition and concrete age. It is also demonstrated, from previously published data that indirect and direct tensile tests reflect different results.

Keywords: Tensile concrete strength, direct tensile test, tensile properties of early age concrete

1. Introduction and background

The existing knowledge about the tensile properties of concrete at 28 day design strength is widely accepted ad research, whereas the requirement for early age properties is limited. Lifting design of precast elements relies upon the properties of concrete at early age as elements are predominantly lifted within 24 hours. The author has conducted numerous tests using compression cylinders as the benchmark concrete property to define the capacity of a cast-in steel insert when a tensile load is applied. The range of cylinder compressive strengths have been in the strength range of 10-42MPa, f_{cm}. Additional tests have been conducted to demonstrate a relationship between naturally cured concrete temperature and cylinder compressive strength with some interesting results, and is a topic of another technical paper. This series of tests in this paper is to demonstrate the relationship of the industry accepted cylinder compressive test to an early concrete strength tensile test.

Concrete is far more sensitive to tensile failure than compressive failure and it is difficult to create a pure shear stress distribution in a test specimen without introducing tension. It has been suggested by Kaplan [1] that initiation of cracking is more dependent on strain than on stress. If a value of induced strain were greater than the ‘tensile strain capacity’ a crack would be initiated. This ‘strain capacity’ can be taken as the strain at the onset of significant cracking or at the limit of proportionality between tensile stress and strain or at some other convenient stress level.

Correlations have previously been obtained between flexural tensile strain capacity and flexural strength for various concrete ages (Welch [2], Olanapo [3]). Approximate short term strain capacity in flexure can be estimated if the modulus of elasticity and strength are known. It has been shown (Brooks [4]) that the thermal strain capacity of concretes of similar strength and workability is related to the type of coarse aggregate used, and there is a good correlation between strain capacity and strength/modulus of elasticity for these results. As far as tensile strength is concerned the splitting tensile test (Carnerio and Barcellos [5]) and the three (or four) point bending test (Hillerborg [6]) have been widely applied. There are some consistent results obtained between flexural tensile strain capacities. But all these tensile tests have the disadvantage that a non-uniform state of stress, which is superimposed over the local stress fluctuations that are caused in concrete. For example, in the splitting test a very steep stress gradient develops, and just below where the load is applied compressive stresses develop perpendicular to the axis of the load. This combination of local stress gradients interacting may result in a variance of crack development dependant on aggregate position, size and volume. Thus it may be suggested that various configurations of calibration of the splitting test machine may be necessary versus concrete mix and type being tested.

Whereas the bending test has its own set of issues to consider, like self weight of the specimen which may alter the post failure (softening) effect of the test result. Again the damage around the applied load may alter the stress gradients, and crack propagation, for different material types. This results in a degree of confinement within the Fracture Process Zone.

Factors effecting the relationship between tensile stress and strain show that this is not a constant value (Welch [2]) and is relative to the test method, the type and size of aggregate, the gauge length, the water/cement ratio, curing conditions, age of concrete and test loading rate.

The tensile strength and tensile strain capacity of concrete are used widely in the assessment of crack occurrence in concrete members. Based on the tensile strain capacity rather than the tensile strength, it is more convenient and simpler to evaluate cracking where the forces can be expressed in terms of linear changes. The tensile strain capacity can be evaluated from the Modulus of Rupture test, where ACI224 Cracking of concrete members in direct tension [7] suggests the following expressions to estimate tensile strength as a function of compressive strength

Modulus of rupture: $f_r = g_r . \sqrt{w_c \cdot f_{cm}^{'}}$ (1)

Direct tensile strength: $f_r = g_t . \sqrt{w_c \cdot f_{cm}^{'}}$ (2)

where:
w_c= unit weight of concrete (kg/m3)
$f_{cm}^{'}$ = compressive strength of concrete at time of test (MPa)
g_r= 0.012 to 0.021 (0.013 – 0.14 is recommended)
g_t = 0.0069

Xie and Liu [8] determined tensile strain capacity from specimens subjected to a direct tensile load. Hunt [9] measured tensile strain capacity from fully restrained concrete prisms in which temperature differentials were induced to bring on the onset of shrinkage cracks. Houghton [10] proposed that the estimated tensile strain capacity is evaluated from the modulus of rupture divided by the modulus of elasticity. Liu [11] developed an approximation method for tensile strain capacity of concrete using compressive strength and the modulus of elasticity. Whereas Wee [12] presented the variation of tensile properties of concrete under various degrees of stress. In BS8110 Structural use of concrete [13] the tensile strain capacity of concrete using granite as a course aggregate was used.

The direct tension test has been given very little research space, which is partly due to the fact that to date because of their inherent ease of setup and test simplicity. However the direct tension tests for establishing concrete capacity of early age concrete designed for lifting precast elements, is the most reliable and relevant test.

1.1 Factors affecting tensile strain capacity

Although it is convenient to assume a constant tensile strain capacity; mix composition, curing conditions, specimen size, gauge length, loading rate and the presence of a notch affect the capacity in different proportions. The tensile stress-strain curve of concrete, figure 2, shows the curve, up to 75%, as almost linear, thereafter the pre-peak nonlinearity due to micro-cracking occurs. The softening response corresponds approximately in two parts, the first a descending one in which strain localization occurs and the second the later descending part with a long tail (Nomura [14]).

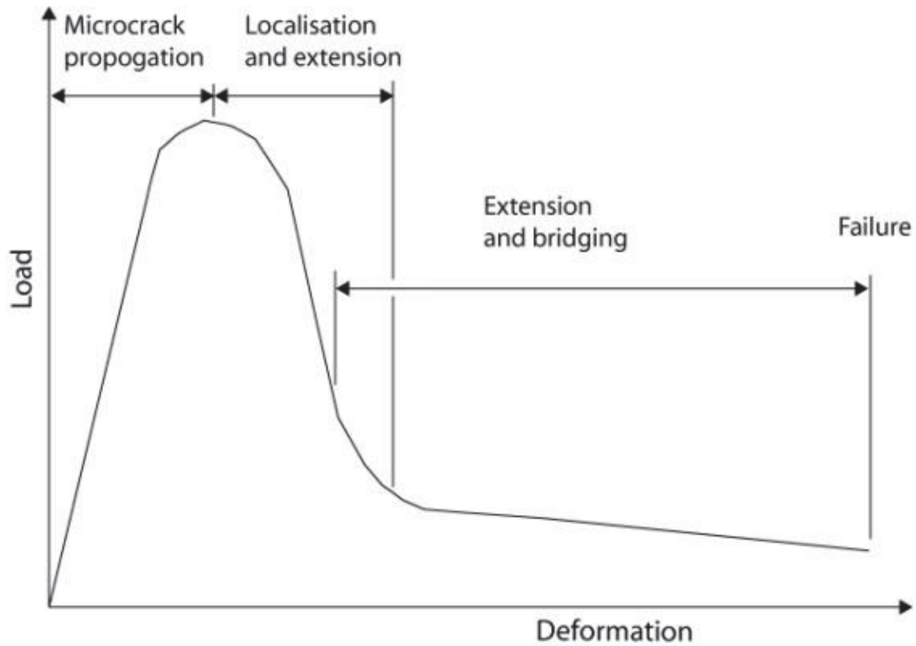


Figure 1 - Simple schematic showing a load deformation curve of concrete in tension (Nomura [18])

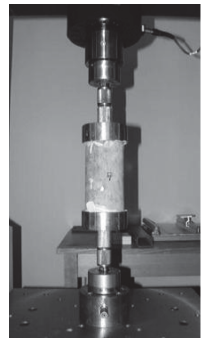
2. Test Method

CONCRETE MIX: The cementitious materials used was GP Portland cement, as per AS3972 General purpose and blended cements [15], and aggregate and sand as per AS2758.1 Aggregates and rock for engineering purposes [16]. Typical w/c ratio of 0.4.

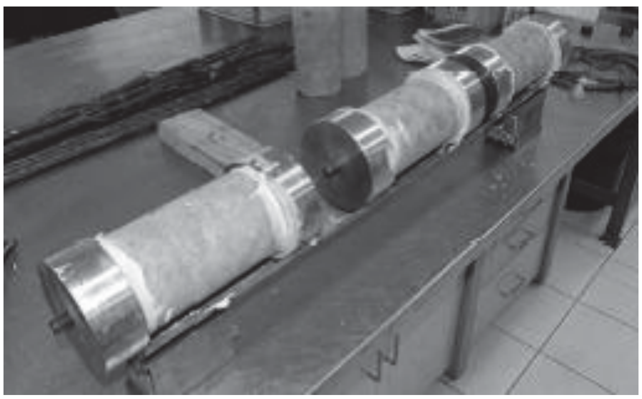
CYLINDERS: Cylinders used for design compressive strength of 20Mpa standard cylinders were used, whereas for design compressive strengths 32MPa and 40MPa a cylinder throat was used. Concrete was prepared in plastic cylinders in accordance with AS1012.8.1 Methods of testing concrete [21], with dimensions of 100mm diameter x 300mm long capped cylinders. The cylinder throats effectively rduced the cylinder diameter by 40mm, with a 30mm reduced section. These throats were used with the effect of placing the tensile fracture of the concrete in this section. Without the use of these throats the tensile fracture was noted close to the end cap. The cylinders were demoulded at time of test and all naturally cured in a stable shaded atmosphere with a temperature range of 10 – 25^{o}C. 30 cylinders were prepared from a single concrete batch, and tested at 18 hours, 3, 7, 14 and 28 days, at a applied load rate of 20kN/minute. At each of the 5 time intervals there was 3 cylinders tested in compression and 3 cylinders tested in direct tension. The time to test the 6 cylinders was 4 hours. After de-moulding, the ends of the cylinder were prepared in accordance with AS1012.8.1 [21].

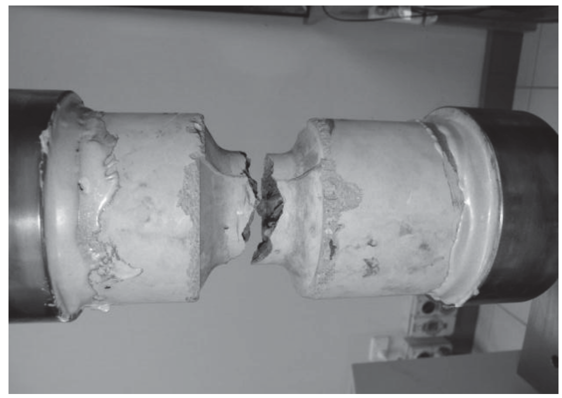
TENSILE TEST: Tensile testing was conducted by capping each end of the cylinders with precision steel caps bonded with epoxy adhesive. The cylinders were then fitted between the universal joints of a tensile testing machine, refer below picture, and loaded at 1.0mm/min until tensile rupture of concrete occurred. Test load and tensile displacement data was recorded for each test.

COMPRESSION TEST: The compression cylinders were tested in the methodology as stated in AS1012.8.1 [17]. Compression testing was conducted by fitting the cylinders with rubber caps at each end, see below picture. Compressive stress was applied at 20MPa/min until the peak load was achieved and compressive rupture of the cylinders occurred.



a) Moulded cylinders **b) Tensile test setup** **c) Compression test setup**





d) Standard cylinder cross sectioned (f'c 20Mpa) **e) reduced section cylinders (f'c 32and 40MPa)**

Figure 2 - Tensile test specimens

3. Test Results

Typical stress-strain curves recorded from the tension tests adopted are shown in Figure 4. As noted by Wee, [12], since concrete is a non homogeneous material, the curves should deviate at higher stress levels. This deviation is dependent on the stress concentrations at the tips of the microcracks, or crack pattern, existing in the test specimen. Load applied at 1mm/min for each specimen.

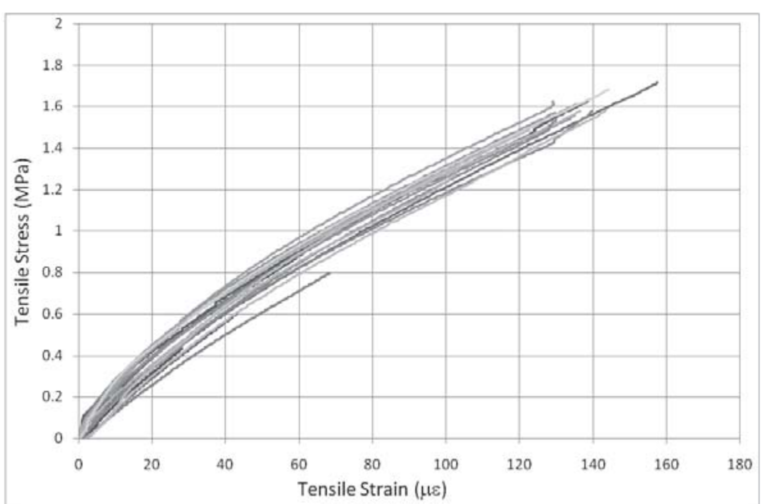


Figure 3 - Stress-strain curves of concrete in direct uniaxial tension

The figures 5, 6 and 7 show the relationship between the compressive and tensile strengths against age of the specimen. As expected, concretes with lower w/c ratios gain strength faster. Mindess [18], recorded for the same w/c ratios, the use of larger aggregate reduces the specific area of the aggregate and hence a lower bond strength, resulting in a reduction of concrete strength. This is shown in figure 6 where the concrete mix proportion is similar, but the smaller the size of course aggregate the greater the tensile strength capacity.

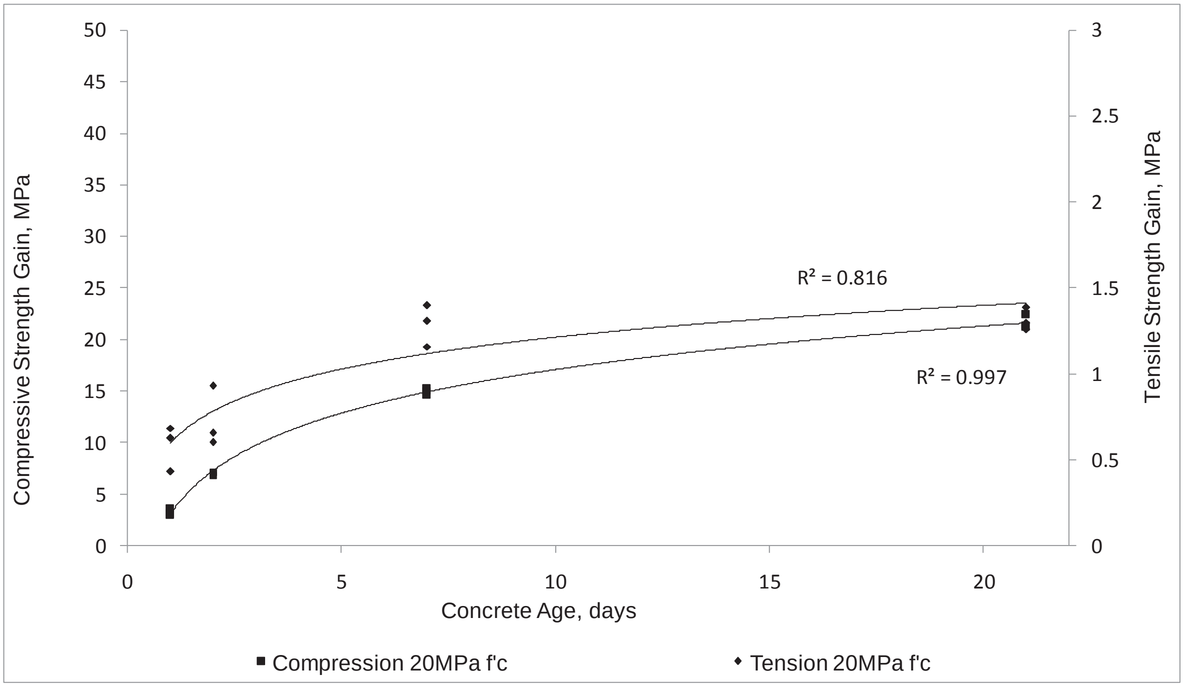


Figure 4 - 20MPa NSC compressive and tensile strength gain and age of concrete

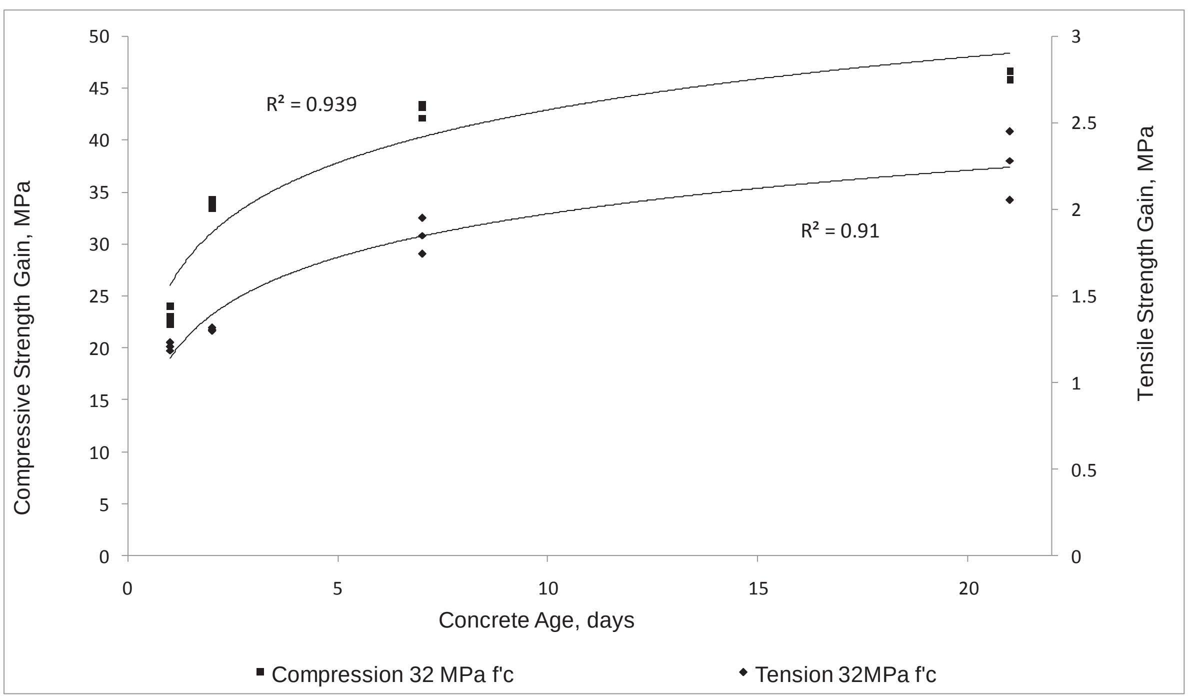


Figure 5 - 32MPa NSC compressive and tensile strength gain and age of concrete

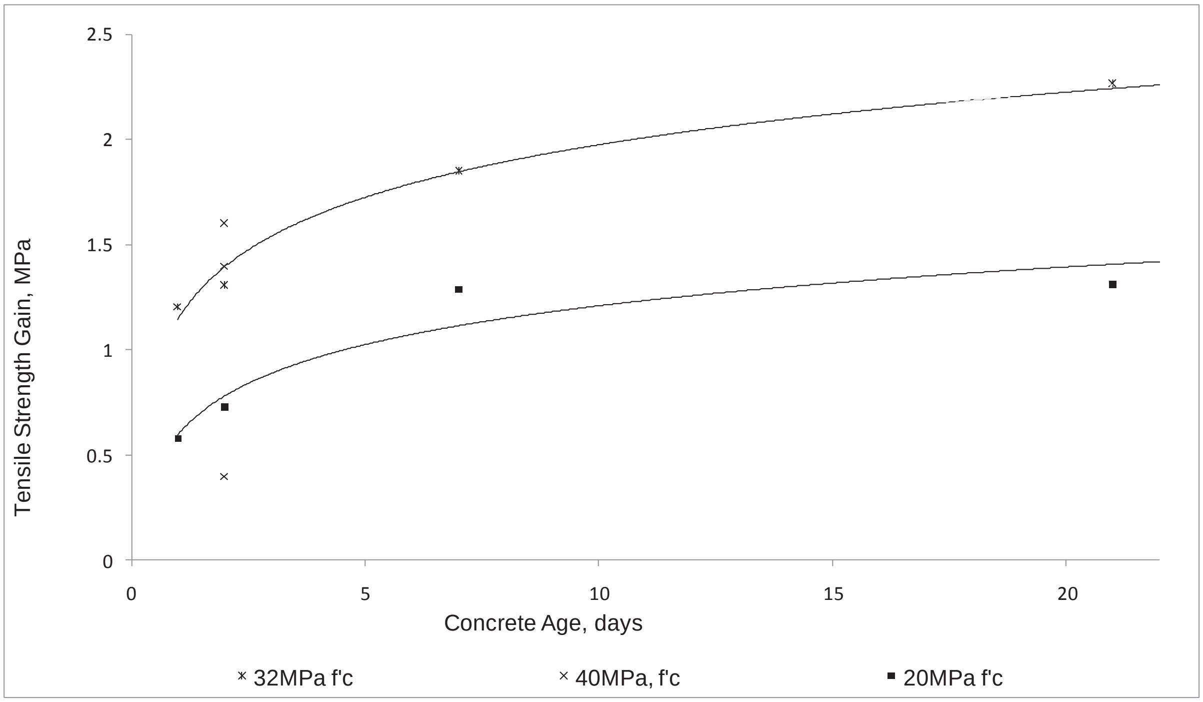


Figure 6 - relationship between tensile strength, age of concrete and concrete mix

Figure 8 displays the relationship between tensile to compressive strength ratio and age of concrete. The tensile to compressive strength ratio decreases as concrete matures. This shows the rate of strength gain in tensile strength is smaller than the increase in compressive strength.

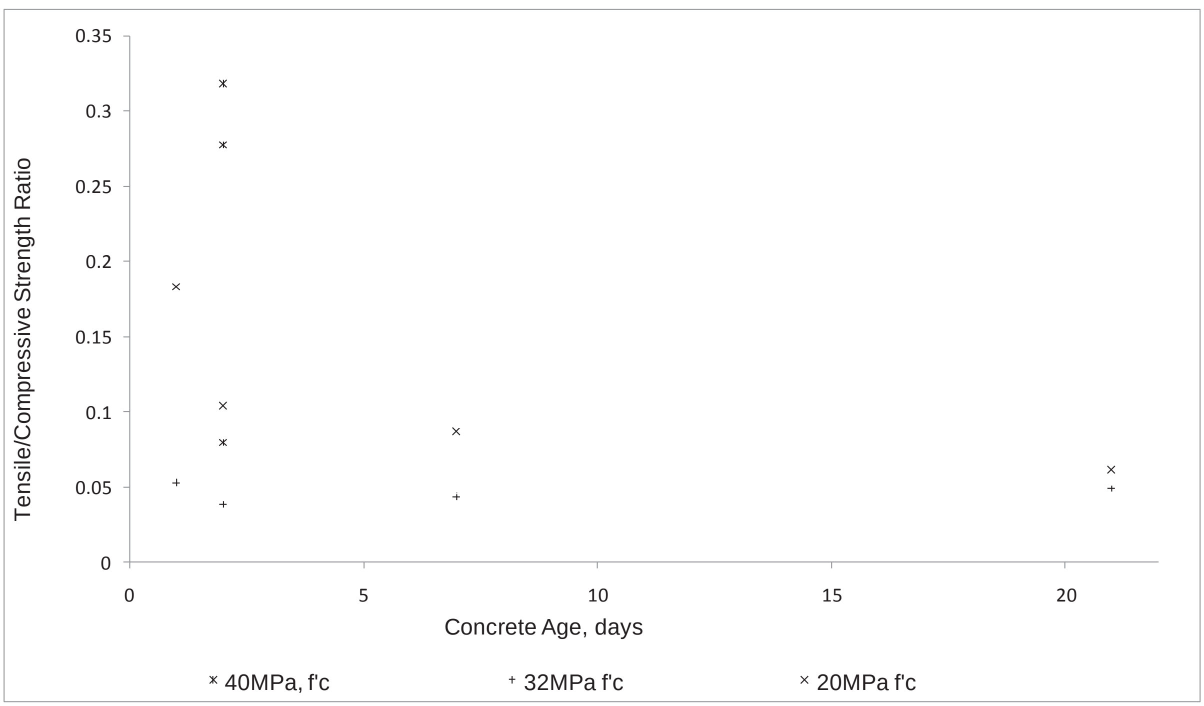


Figure 7 - Tensile/compressive strength ratio against compressive strength

The relationship between tensile to compressive strength ratio and compressive strength of the 3 types of concrete compressive design strength are depicted in the above figure.
The tensile to compressive strength ratio decreases as compressive strength increases, or concrete ages. By implication the tensile strength gain is smaller than the increase in compressive strength. For this test (between 20-40MPa design strength) the tensile to compressive strength ratio varies from 0.04 to 0.06, whereas the data from Mindess [18], ranged from 0.1 to 0.06.

For concretes that yield lower tensile strength the smaller value of tensile to compressive strength ratios. This finding is supported by Wee at. Al. [12].

4. Conclusion

Based on the mix proportions, cementitious materials used and the experimental method adopted in this test analysis, the following conclusions can be made:

1 - The tension test procedure, which is designed for ease of use, and is required to have a low coefficient of variation and accuracy of concrete tensile reading to be meaningful, produces a larger distribution of results than other direct methods of testing

2 – For different design strength concrete mixes, the tensile strength gain rate is different

3 – Further experimentation to establish tensile strength gain in relation to the onset of hydration is necessary to further the tensile properties of precast concrete

4 – Tensile strength of concrete increases with curing age at a lower rate than compressive strength. The tensile to compressive strength ratio varies between 0.08 at low compressive strength to 0.04 at higher compressive strength.

5 – The ability to measure concrete strength gains reliably, will increase efficiencies in the precast yard

This uniaxial tension test has not been fully explored to produce a reliable and consistent indication of concrete fracture mechanisms. The uniaxial tension test could be the most fundamental test to determine the fracture properties of concrete, and especially at early age concrete strengths. Further work to compare mix proportions, effects of curing age against tensile strength gain. Size effect is another consideration not assessed during this test.

5. Acknowledgements

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6. References

1. Kaplan, M, Strains and stresses of concrete at initiation of cracking and near failure. Journal of Concr. Inst. Proc. 1963, 60, No 7, 853-880

2. Welch, G. B., Tensile strains in unreinforced concrete beams. Magazine of Concrete Research., 1966, 18, No. 54, March, 9 – 18.

3. Olanapo, I, Cracking and failure in plain concrete beams. Mag Concr. Res., 1964, 18, No 54, March, 9-18

4. Brooks, J.J., Influence of lightweight aggregates on thermal strain capacity of concrete, Mag. Concr. Res. 1987, 39, No. 139, June, 60-72

5. Carneiro, F, Barcellos, A, Resistance a la traction des betons. Bulletin RILEM 1953;I (13): 97-108

6. Hillerborg, A, The theoretical basis of a method to determine the fracture energy Gf of concrete. Mater Struct. (RILEM) 1992;8:291-6

7. ACI (American Concrete Institute Committee).1992. ACI224.2R-92, Cracking of concrete members in direct tension, Farmington Hills (MI): American Concrete Institute.

8. Xie & Lee

9. Hunt, J.G, A laboratory study of early age thermal cracking of concrete, Cement and Concrete Association, London, 1971

10. Houghton, D.L, Determining tensile strain capacity of mass concrete, J. Am. Concr. Inst. 73 (6) (1976) 691-700

11. Liu, T.C, McDonald, J.E, Prediction of tensile strain capacity of mass concrete, J. Am. Concr. Inst. 75 (3) (1978) 192-197

12. Wee, T.H, Lu, S, Swaddiwudhipong, S, Tensile strain capacity of concrete under various states of stress, Mag. Concr. Res. 52 (3) (2000) 185-193

13. British Standards Institute, BS8110: Structural use of concrete

14. Nomura, N, et. al., Correlation of fracture process zone and tension softening behaviour in concrete. Cem. Concr. Res., 1991, 21, No 4, 545-550.

15. Standards Australia, 2010. AS3972 General purpose & blended cements, Sydney Australia, Standards Australia.

16. Standards Australia, 2009. AS2758.0-2009 Aggregates & rock for engineering purposes, Sydney Australia, Standards Australia.

17. Standards Australia, 2000. AS1012.8.1-2000 Methods of testing concrete, Sydney Australia, Standards Australia.

18. Mindess, S, Young, J, Concrete, Prentice Hall, Englewood Cliffs, NJ 1981